

Magnetic field measurements in white dwarfs. Magnetic field, rotation and spectrum of 40 Eri B

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Abstract. This paper describes results of magnetic field measurements of white dwarfs carried out on the 6-m telescope for the last years. A magnetic field of about $B_e \approx 28$ kG has been discovered in the degenerate star WD 1953–011 which has been selected from high-resolution spectroscopy of non-LTE $H\alpha$ core by Koester et al. (1998). A rotational period of WD 0009+501, 1.83 hours, has been discovered, the average magnetic field of the star is $\langle B_e \rangle = -42.3 \pm 5.4$ kG and its semi-amplitude of the rotational variability is 32.0 ± 6.8 kG. The variable magnetic field of the bright normal (non-magnetic) degenerate star 40 Eridani B was confirmed in January 1999 by Zeeman time-resolved spectroscopy. Both the $H\alpha$ and the $H\beta$ lines give about the same results, we have selected two best periods in the magnetic field variability, $2^h 25^m$ and $5^h 17^m$. The semi-amplitude of the rotational variations $B_{max} \approx 4000 \div 5000$ G and the average field is about zero ± 500 G. If the magnetic field of 40 Eridani B is a central dipole, then the rotational axis inclination to the line of sight is $i \sim 90^\circ$, and the magnetic axis inclination to the rotational axis is about the same, $\beta \sim 90^\circ$. For the first time an ultra-high signal-to-noise spectrum of the white dwarf has been obtained ($S/N > 1000$). We have found in this hydrogen-rich DA white dwarf 40 Eridani B (16500 K) that helium abundance is low ($N(\text{He})/N(\text{H}) < 10^{-7}$), but the spectrum is rich in ultra-weak absorption lines of metals in low ionization states. It was proposed that these lines were produced in both circumstellar and interstellar gas. The gas may be supplied by accretion from interstellar medium and from the dM4e companion 40 Eridani C with an accretion rate $\dot{M}_a \sim 10^{-19} M_\odot/\text{y}$. The accreting gas may form a circumstellar rotating envelope in the magnetosphere at a distance of $\sim 4 \cdot 10^{11}$ cm.

Introduction

The magnetic observations of dwarfs (WDs) have been carried out in the Laboratory of Stellar Physics of SAO since 1989. Originally the tasks were to detect magnetic fields in normal DA WDs observing them with an accuracy of about a few kG and to study the distribution of WDs over their surface magnetic fields (magnetic field function), to observe known magnetic WDs in order to find their rotational periods and to study the magnetic fields – rotation relation. Until 1995 the observations were fulfilled with the hydrogen-line magnetometer of the 6-m telescope (Stol', 1991; Bychkov et al., 1991; Shtol' et al., 1997; Fabrika et al., 1997). These observations and such observations of other authors (mainly by Schmidt & Smith, 1995) have shown that WDs with magnetic fields $B \gtrsim 10$ kG are not numerous.

It was found in the later statistical studies (Fabrika & Valyavin, 1999; Valyavin & Fabrika, 1999) that the frequency of magnetic $B \gtrsim 1$ MG WDs is about 2 % among hot (young stars) and it is about 20 % among cool (old) stars, i. e. the magnetic field does certainly evolve in WDs. It was also found that the

magnetic field function is a power one, $P_B \sim B^{-\alpha}$, with a power index $\alpha \approx 1.3$. Normalization properties of the magnetic field function allowed to estimate the frequency of magnetic WDs in the weak-field limit. We may expect the minimum *surface* magnetic field strength to be 1–10 kG in hot WDs ($T > 10000$ K) and in cool WDs ($T < 10000$ K) it is 10–50 kG. To confirm these conclusions by direct observations and to study the weak-field part of the magnetic field function, we decided to observe the brightest DA WDs with a higher accuracy.

Zeeman spectroscopy with the Main Stellar Spectrograph

In 1995–1997 Zeeman spectral observations of bright DA WDs were carried out on the Main Stellar Spectrograph (MSS) of the 6-m telescope with a circular polarization analyzer (Valyavin et al., 1997; Fabrika & Valyavin, 1999). The time-resolved spectroscopy with 3 – 5 min exposure times was aimed at both detection of possible rotational variability in individual spectra and deriving high accuracy estimates of av-

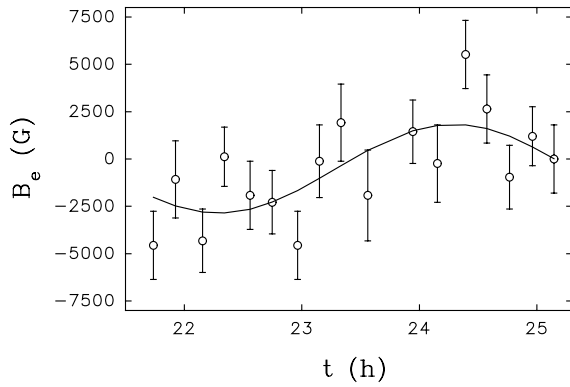


Fig. 1: The time-resolved Zeeman spectral observations of 40 Eridani B with the Main Stellar Spectrograph obtained on December 5, 1995

erage magnetic field in sum spectra. Each image in this mode of observations consists of two simultaneous spectra of opposite circular polarization which are splitted in the analyzer. Two different orientations of the first quarter-wave plate are used to record opposite circular polarization spectra at the same place of the CCD detector in two adjacent exposures. We used this configuration of the higher spectral resolution with a hope to detect magnetic shifts in narrow non-LTE H α profiles of DA ($8000 \div 22000$ K) WDs. It was expected that observations in this mode could provide the desired accuracy of about 1 kG. In some brightest WDs such an accuracy has actually been reached, however without positive detections. For example in time-resolved Zeeman spectroscopy of WD 0713+584 we did not detect any periodical signals during a time of observations of 113 min. The total average effective magnetic field estimate has been obtained in this star particular $B_e = 0.1 \pm 1.0$ kG.

The brightest degenerate star 40 Eri B was observed in the same mode on September 14, 1995. The average magnetic field, $B_e = 0.5 \pm 0.37$ kG, during a time of observations of 81 min has been found. However in another observing run, on December 5, 1995, we found about 4 -hours' sinusoidal variations of the effective field of 40 Eri B during 215 min of observations. These observations are displayed in Fig. 1. They consist of 54 (3 min) individual measurements averaged in 17 bins. The best fit is $B_e = A + B \cos(2\pi t/P + \phi)$ with $A = -510 \pm 520$ G, $B = 2300 \pm 700$ G and a period $P \approx 4$ hours. It was concluded that for reliable detection of magnetic field and rotational period in 40 Eri B such mode of observations must be continued.

The MSS observations of 40 Eri B might be interpreting not only as the 4 - hours' periodical variations. The period suspected cannot be considered as reliable, because the time of observations is comparable with the period, the scatter of the individual

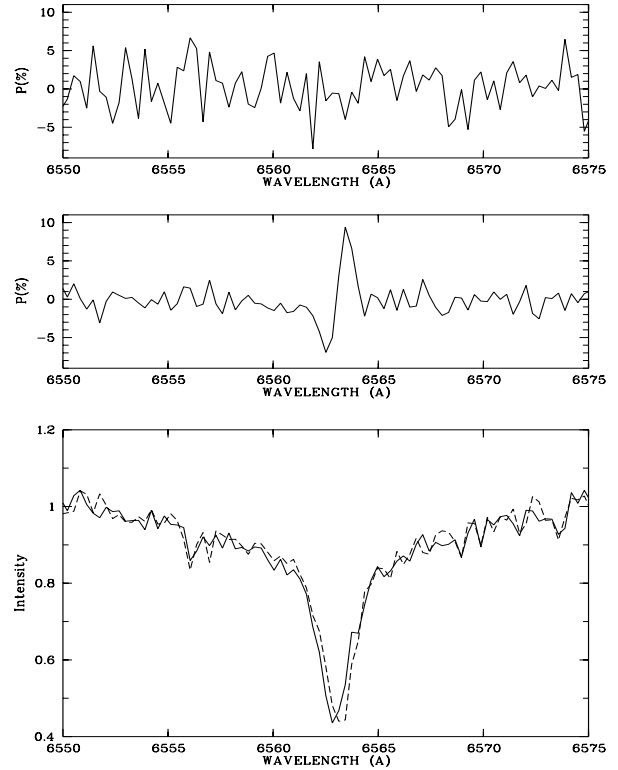


Fig. 2: Opposite circular polarization spectra of 40 Eridani B in the region of the H α line core and corresponding polarization (bottom and middle) obtained from the individual spectra (Fig. 1) showing the maximal positive polarization. Atmospheric water lines around H α are also visible. At the top we show polarization obtained from the individual spectra of the zero polarization “cross-over points”

points is high, and one can say only that a variability of the magnetic field was detected that time. In addition we found other periodical signals in those data, one of them was ≈ 37 min. There was also a period of about 10 min detected in the previous observing run on September 14, 1995. Indeed, we could say that some probable magnetic field variations were registered that time.

In order to demonstrate the magnetic shift of the H α line in opposite circular polarization spectra, we present here the results of analysis of two sum double-polarized spectra obtained from the individual spectra for the December 5, 1995 observing run. The first sum spectrum consists of individual spectra showing the maximal positive polarization (the top points in Fig. 1, situated between the 24th and 25th hours of the time axis), and the other spectrum consists of the zero polarization spectra (the “cross-over points” in Fig. 1, situated between the 23th and 24th hours). In Fig. 2 two spectra of different polarization from the

first summed image in the region of the $H\alpha$ line are shown (bottom). The magnetic shift in $H\alpha$ is clearly visible. There are some H_2O atmospheric absorption lines in the region not showing a shift. The result of subtraction of these spectra, i. e. the polarization (V-parameter) is shown in the middle of Fig. 2. The typical S-wave polarization in the line profile is detected. At the top of Fig. 2 the polarization obtained from the second (“cross-over”) image is shown. No detectable polarization is observed there.

Observations with the SP-124 spectrograph

In 1997 we changed the observational mode to the medium resolution spectrograph SP-124. This spectrograph was equipped with a PM-CCD (1024x1024) providing spectra of a high quality (Neizvestnyi et al., 1998) and with a new polarimetric analyzer having a better transparency (Bychkov et al., 2000). The analyzer is equipped with a rotatable quarter-wave plate. The spectral resolution in this mode is $5\text{--}6 \text{ \AA}$ ($2.3 \text{ \AA}/\text{pix}$). With such a resolution we have lost the possibility of making measurements of the narrow non-LTE $H\alpha$ peak, instead we can study two hydrogen lines $H\alpha$ and $H\beta$ simultaneously, measuring central cores of these lines. Otherwise the method is the same, the left- and right-circular polarized Zeeman spectra are obtained simultaneously on the detector. The main advantage of this mode is that one can obtain Zeeman spectra of WDs with high signal-to-noise because of the better CCD cosmetic and stability (and the lower spectral resolution), besides it provides for recording of two hydrogen lines in the spectrum.

Table 1: Results of magnetic field measurements

Target(WD)	N	JD +2450000	$B_e(\text{G})$	$\sigma(B_e)(\text{G})$
2032+248	2	684.342	810	4200
2326+049	3	684.379	150	2400
0148+467	2	684.433	-390	4500
1126+185	2	950.841	-3200	10500
1953-011	6	357.479	28000	6000

In Table 1 we present new results of magnetic field measurements in 5 DA degenerates in the moderate resolution mode. N is the number of spectra obtained. We found no magnetic field in four stars, but a reliable magnetic field has been detected in WD 1953-011. In a massive Zeeman spectroscopy of DA WDs Schmidt & Smith (1995) found a magnetic field, $B_e = 15.1 \pm 6.6 \text{ kG}$, of WD 1953-011. This result suggested WD 1953-011 to be a magnetic WD candidate. This star was also suspected as magnetic

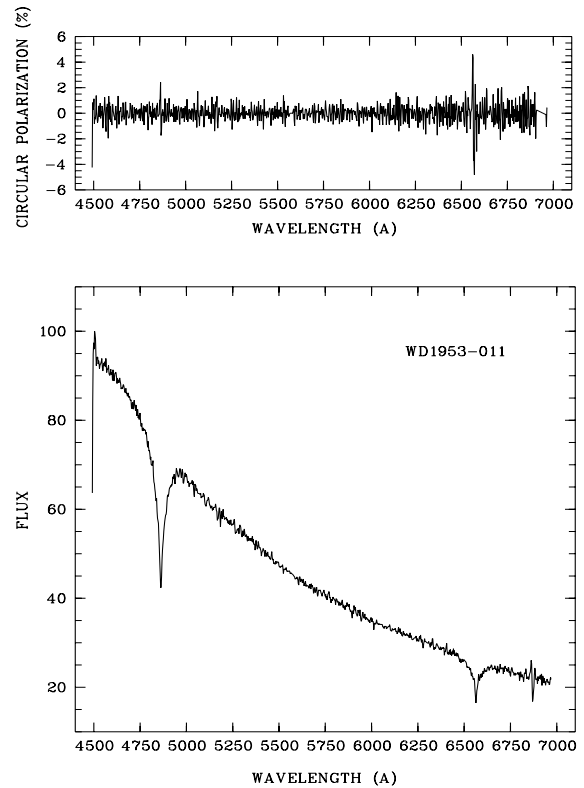


Fig. 3: A spectrum and circular polarization of the magnetic degenerate WD 1953-011

by Koester et al. (1998) in their high-resolution spectroscopy observations of the NLTE $H\alpha$ cores in DA WDs. In this program of searching for rotation in WDs the narrow $H\alpha$ cores are fitted with broadened NLTE models, and thus projections of rotation velocities are derived. In normal DA stars the rotation velocities are extremely small with typical upper limits for $v \sin i$ of about 15 km/s. In WD 1953-011 a formal $v \sin i$ has been found to be $173 \pm 10 \text{ km/s}$, however a clear Zeeman splitting has been detected in two independent spectra. The splitting corresponds to a surface magnetic field $B_s \approx 93 \text{ kG}$ (Koester et al., 1998). In our observations the magnetic field of WD 1953-011 was firmly detected, $B_e = 28 \pm 6 \text{ kG}$. In Fig. 3 the spectrum (the sum of two Zeeman spectra) of WD 1953-011 is shown as well as the circular polarization derived from the Zeeman spectra. The S-wave polarization pattern is clearly seen both in $H\alpha$ and $H\beta$.

The magnetic nature of WD 1953-011 was thus confirmed in direct Zeeman spectroscopy. Koester et al. (1998) discussed the fact of considerable systematic difference in magnetic fields estimated in high-resolution spectroscopy from $H\alpha$ NLTE core splitting and those found in Zeeman spectroscopy of moderate resolution. This could be an effect connected

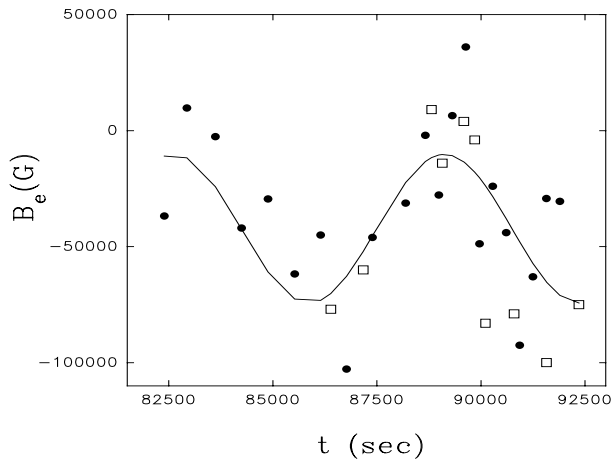


Fig. 4: Time-resolved Zeeman spectroscopy of the magnetic white dwarf WD 0009+501. The results by Schmidt & Smith (1994) are imposed on our data, they are indicated by open squares

here with different parts of the line profile which are measured by these different methods. However it is hardly probable for a magnetic field to be notably different depending on the star atmosphere height. The longitudinal magnetic field varies with rotational phase over wide limits, from 0 to almost the polar field B_p , depending on orientation; at the same time the surface (integral) field varies with rotation over much narrower limits. In a model of a dipolar magnetic field with occasional orientation of the dipole axis the surface and longitudinal (effective) magnetic fields are related by a statistical relationship (Angel et al., 1981) $B_s \approx 3B_e$. In this particular star WD 1953–011 our result, $B_e \approx 28$ kG, and that by Koester et al. (1998), $B_s \approx 93$ kG, agree well with the statistical relation.

The known magnetic degenerate star WD 0009+501 was observed on September 1, 1999 in the same mode, the time-resolved Zeeman spectroscopy. WD 0009+501 has been discovered as magnetic by Schmidt & Smith (1994). In 12 observations for 4 observing nights they found a variable magnetic field in the range $B_e = +9 \div -100$ kG with $\sigma(B_e) = \pm 8 \div 15$ kG. The field obviously varies because of rotation of the star. A power spectrum analysis has shown a variety of peaks between the 2-nd and 20th hours, with some preference for shorter periods (Schmidt & Smith 1994). There were about 12 minutes between the spectra in an observational pair, and no variability of magnetic field was detected inside the pairs, but obvious variations were detected in adjacent observations separated by about 5 hours. They observed a nearly full amplitude of variability (about 90 kG) during an interval of 5 hours.

Our observing run of WD 0009+501 consists of 21

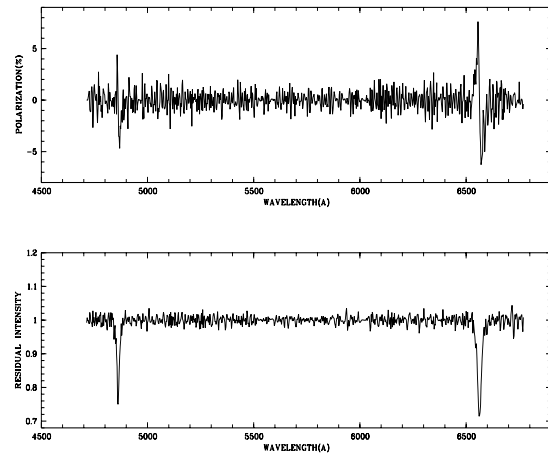


Fig. 5: A spectrum and circular polarization of the magnetic degenerate WD 0009+501

continuous Zeeman spectra, the first 10 spectra were taken with a 10 -minut of exposure, and the next 11 spectra with 5 -minut of exposure. Results of measurements of the $H\alpha$ line are shown in Fig. 4. The total profile of the line in opposite polarization spectra was measured by a Gauss-analysis. The measurements of $H\beta$ are not shown here, they are of about the same behaviour, but less accurate. The observations cover a 2.6 -hours' interval. The variability of magnetic field is clearly seen in Fig. 4 (filled circles). It was not possible to derive the period accurately from this observational series alone. One can conclude from our data only that the rotational period of WD 0009+501 is about 2 hours. However with addition of the data by Schmidt & Smith (1994) and analyzing these total data together we have found the rotational period, it is 1.83 hours. The same unique period has been identified in their and our power spectra. In Fig. 4 the 10 close separated in time observations by Schmidt & Smith (1994) are shown as open squares. They have been shifted by arbitrary phase of the 1.83-hours period. The curve in the figure is sinusoidal fitting of our data. The average magnetic field is $\langle B_e \rangle = -42.3 \pm 5.4$ kG, the semi-amplitude is 32.0 ± 6.8 kG.

In Fig. 5 we present both the summed unpolarized spectrum of WD 0009+501 (bottom) consisting of 8 spectra showing maximal magnetic field and the corresponding circularly polarized spectrum (top). The polarization is clearly seen both in $H\alpha$ and $H\beta$.

Magnetic field of 40 Eridani B

The brightest DA star 40 Eri B was observed in the SP-124 mode on January 25, 27, and 28 1999 (here-

after — the first, second and third night). The aim was to check the magnetic field variability suspected in our observations in the MSS-mode earlier (see above). A total of 66 Zeeman images were taken (correspondingly 10, 26 and 30 images on these particular nights) with an exposure time of 5 minutes. On the whole the observations lasted for 70, 175 and 192 minutes, respectively on these nights, but they included the time for rotation of the quarter-wave plate and other observational operations. We rotated the plate every 5 (sometimes 10) exposures. This operation is very important for both to take correctly into account many systematic effects connected with nonideal orientation of the slit and the polarimetric analyzer and to project the spectra of opposite polarization onto the same pixels of the detector. Nevertheless, in the case of magnetic variables like our target 40 Eri B is, this procedure alone can not solve the problem of systematic shifts. For this reason we took spectra of standard stars in the same mode just before and after the observations of 40 Eri B. As standards, we used different bright stars which were chosen depending on a current observational program and situation. These are the cool stars ϵ Tau, α Cep or neighbouring stars. The instrumental line shifts in opposite polarization spectra have been measured in the standards to control any possible systematic shifts with time. In the first star all lines have been measured by the cross-correlation method in restricted ($\approx 100 \text{ \AA}$) spectral regions around $H\alpha$ and $H\beta$. Other standard stars are of about the same spectral class as the target or have clearly visible hydrogen lines, so we have measured these two lines in their spectra. One cannot expect effective magnetic fields $> 1 \text{ kG}$ in bright stars selected by chance (Monin et al., 2000), and all these stars could serve as standards to control our “magnetic zero” variability with an accuracy of $\approx 1 \text{ kG}$ or better. Instrumental shifts of about $1 - 3 \text{ kG}$ were really detected in these observations for $2 - 3$ hours of observing, and the data were corrected for these shifts by a linear interpolation.

Two hydrogen lines $H\alpha$ and $H\beta$ have been analysed in 40 Eri B. All the spectra have been normalized with the same window, 180 \AA . Relative shifts in the circular polarized spectra have been measured by the Gauss-analysis method. Only central line cores of about 30 \AA in width were thus measured in the normalized spectra. Both the normalization procedure and the spectral filter parameters were optimized and they were used in a strictly the same way in all the spectra. Not all the spectra we obtained were finally used in magnetic field measurements. The target is low enough at the 6-m telescope latitude (the zenith distance is 51° at the culmination). We observed 40 Eri B around the culmination and tried to obtain the observations as long as possible, nevertheless, depending on weather conditions not all the spectra

were obtained with a desired quality ($S/N > 80 \div 90$ in an individual spectrum of one polarization). We selected the best spectra *before* the measurements of magnetic field, and only the ones where the hydrogen line cores were not distorted by cosmic ray particles. Particle traces in the steep line cores, even being corrected, may result in distortion of the line shifts.

Results of magnetic field measurements in $H\alpha$ line from individual Zeeman spectra of 40 Eri B are shown in Fig. 6 for the first (top) and the third (bottom) nights of the January 1999 observing run. The crosses indicate the magnetic field of the target, the stars indicate that of the standards. On the first night the stars α Cep (before) and ϵ Tau (after) were observed as standards. On the third night there were neighbouring stars, a star situated about $19'$ to north (before) and 40 Eri A (after). The first star was unfortunately not bright enough on the last night to provide a desired accuracy of the zero-field point ($< 1 \text{ kG}$). This may result in some uncertainty as a total shift (a linear trend) in calibration of the first points in this series of observations. One can see the variable magnetic field in 40 Eri B detected in $H\alpha$.

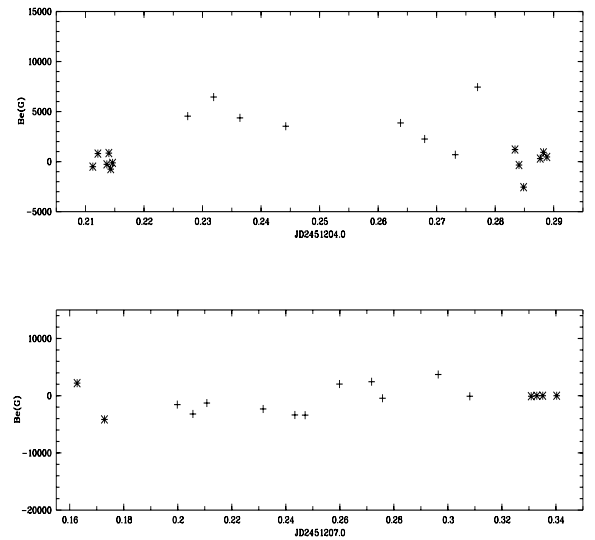


Fig. 6: The $H\alpha$ line magnetic field variability of 40 Eridani B obtained on the first and third nights of observation

Power spectrum analysis of the data from all three nights together, both Fourier and a least-squares search for sinusoidal signals display several peaks from about 2 hours to 5 – 6 hours. These peaks are not independent, they are on a common origin consisting in variable, periodical and probably, not sinusoidal signal. Magnetic phase curves in $H\alpha$

and $H\beta$ of two best periods, $2^h 25^m$ and $5^h 17^m$, are displayed in Fig. 7 and 8 respectively. Both the $H\alpha$ and the $H\beta$ lines confirm the periodical variations, they are about the same both in phase and in amplitude, though the scatter in the $H\beta$ data is greater. The individual data are presented by open circles, the mean values averaged in the phase bins $0.1\Delta\phi$ with their r.m.s. errors are shown by filled circles. We present in these figures also the sinusoidal fitting of the data as $B_e = A + B \sin(2\pi t/P + \phi_0)$. The phase ϕ_0 was fixed the same in both lines. The parameters of the curves have been found as follows.

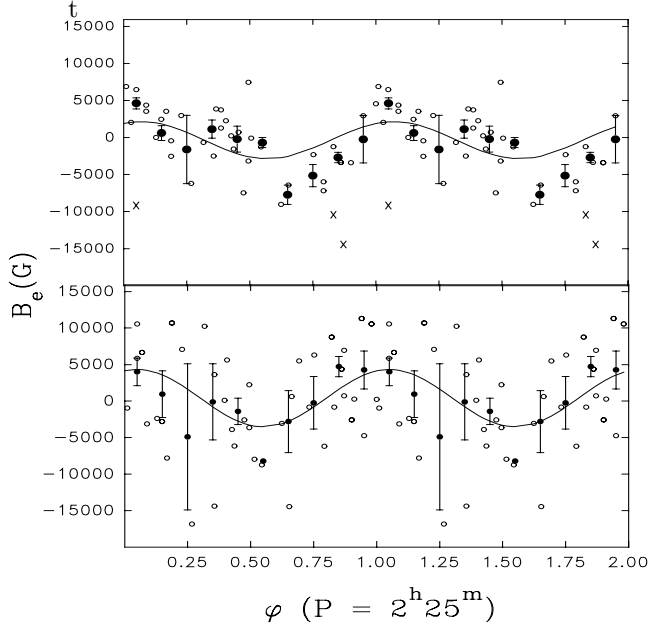


Fig. 7: The first period magnetic field phase curve for $H\alpha$ (top) and $H\beta$ (bottom)

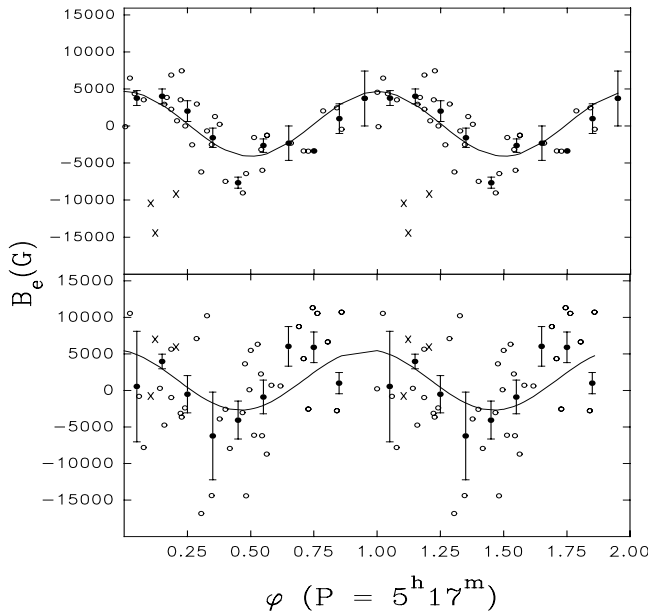


Fig. 8: The same as in Fig. 7 for the second suspected period

$P = 2^h 25^m$

$H\alpha$: $A = -300 \pm 550$ G, $B = 2500 \pm 900$ G,

$H\beta$: $A = 400 \pm 1000$ G, $B = 4000 \pm 1400$ G,

$P = 5^h 17^m$

$H\alpha$: $A = 300 \pm 550$ G, $B = 4400 \pm 700$ G,

$H\beta$: $A = 400 \pm 900$ G, $B = 4000 \pm 1400$ G.

A number of possible systematic shifts (for instance, the atmospheric dispersion) may influence the results changing the positions of these two lines in antiphase, because the lines are situated at different edges of the spectral range covered in our spectroscopy. The correlated variability means that systematic effects do not distort the results notably. However 3 points do not agree with the $H\alpha$ magnetic curves, but agree well with those in $H\beta$. They are marked by the crosses in Figs. 7, 8. They belong to the second night. We can not exclude here the influence of systematic effects.

The setting the equalizing of the zero phases to be equal in $H\alpha$ and $H\beta$ resulted in the sinusoidal fits parameters are not best. For instance, the $H\alpha$ magnetic field amplitude in the first period has been found to be too small in the formal fit. The zero phases are really slightly different in $H\alpha$ and $H\beta$, and this is due to the individual data scatter. We conclude that the $H\alpha$ and $H\beta$ data both show the same periodical variations of the effective magnetic field. The semi-amplitude of the variations, $B_{max} \approx 4000 \div 5000$ G, and average field is about 0 ± 500 G. The direct average magnetic field derived from the $H\alpha$ data only (without the 3 measurements indicated by crosses in the figures) is $\langle B_e \rangle = -200 \pm 500$ G. The ratio $B_{max}/\langle B_e \rangle$ is found to be very high. From the data in Fig. 7, 8 One can make a conclusion on the star and its magnetic field orientation. If the magnetic field of 40 Eridani B is a central dipole, then the rotational axis inclination to the line of sight is high, $i \sim 90^\circ$, and the magnetic axis inclination to the rotational axis is about the same, $\beta \sim 90^\circ$.

We may conclude that these new data confirm the previous result obtained in the 1995 observations with MSS, where we found a variable magnetic field in 40 Eri B with a semi-amplitude of 2300 ± 700 G changing on a time-scale of about 4 hours. However we cannot determine firmly a real sole period of the variability. We could select two possible periods in the variability. The first one ($2^h 25^m$) was determined with a much better accuracy than the second one ($5^h 17^m$). The latter period is longer than the longest observational series on the second and third nights (none of the observations covers the whole 5

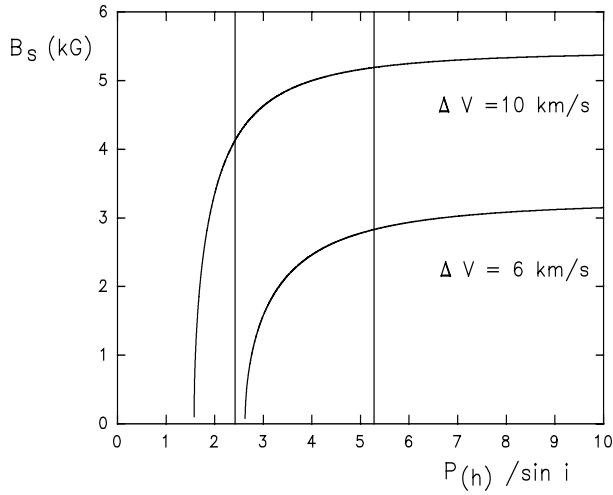


Fig. 9: The relation between surface magnetic field and rotational period of 40 Eridani B. The curves correspond to the upper limits on the total width of the non-LTE H α core, vertical lines indicate the two rotational periods derived in this paper. The permitted region is located below upper curve and to the right of the left vertical line

hours' period, they appear as fragments of the magnetic phase curve in Fig. 8). Nevertheless, the 5 hours' phase curve demonstrates that if the rotational period of 40 Eri B is $\gtrsim 5$ hours, the magnetic curve must be non-sinusoidal (a non-dipolar magnetic field).

The rotation and the magnetic field could be tested together through their impact on the line broadening. The two effects broaden the central core of the H α line independently. The surface magnetic field splitting is $\Delta V_{\text{mf}} = 1.84 B_s \text{ km/s kG}$. The rotational broadening is $\Delta V_{\text{rot}} = V_{\text{rot}} \sin i = 4\pi R / (P / \sin i)$, where R is the radius and P is the period. The total broadening $\Delta V = \sqrt{\Delta V_{\text{mf}}^2 + \Delta V_{\text{rot}}^2}$ is the observed quantity. In high-resolution spectroscopy the central H α core profile being fitted to broadened NLTE models yields an estimate of the velocity ΔV . Heber et al. (1997) presented such a study of 40 Eri B; they found the broadening of less than $\Delta V < 8 \text{ km/s}$ to be the upper limit at a 3σ level. We show in Fig. 9 the relation between B_s and $P / \sin i$ for this star, where the radius $R = 8.9810^8 \text{ cm}$ (Reid, 1996) is accepted. Two curves in the figure indicate the total broadening $\Delta V = 10$ and 6 km/s .

The permitted region for the magnetic field and rotation of 40 Eridani B is one below the curves. We present these two curves keeping in mind that the magnetic broadening can be variable with rotational phase. It varies depending on the dipole parameters and on the unknown phase of the suspected (2–5 hours') rotational period, when the spectra for

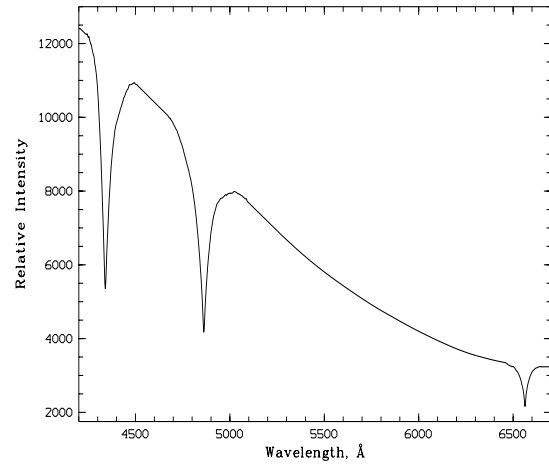


Fig. 10: The total spectrum of 40 Eridani B obtained from 3 nights

the $v \sin i$ analysis were taken (Reid, 1996; Heber et al., 1997). The surface magnetic field strength may change by a factor of $1 \div 2$ in the course of rotation. This estimate follows from the study of magnetic Ap stars by Mathys et al. (1997). They collected data on 42 well-studied magnetic Ap stars, their magnetic curves and the mean magnetic field modulus. The ratio $q = \langle B \rangle_{\text{max}} / \langle B \rangle_{\text{min}}$ of the observed maximum and minimum values of the mean surface magnetic field modulus varies from star to star over the limits indicated above. About 60 % of the stars have $q = 1.0 - 1.1$, and the other stars have this ratio $q = 1.1 - 1.9$. Taking into account the magnetic broadening as a probable variable contributor to the total line broadening and $\Delta V < 8 \text{ km/s}$ as the observed 3σ upper limit (Heber et al., 1997), we can adopt $\Delta V < 10 \text{ km/s}$ as a very probable upper limit of the H α core width in this star. Two vertical lines in Fig. 9 correspond to the rotational periods $2^{\text{h}} 25^{\text{m}}$ and $5^{\text{h}} 17^{\text{m}}$ (at $\sin i = 1$), which we discussed above. The permitted region for 40 Eridani B is that both below the upper curve and to the right of the $2^{\text{h}} 25^{\text{m}}$ vertical line. We can conclude that the high-accuracy Zeeman observations must be continued to clarify the rotation of the star and its magnetic field curve. Fig. 9 demonstrates the possibilities. In the near future we will be able to know both the rotational period and the magnetic field structure and orientation in 40 Eridani B.

Spectrum of 40 Eridani B with ultrahigh signal-to-noise

The presence of heavy elements in the atmospheres of very hot DA (H-rich) white dwarfs is well established. These are a group of stars with effective temperatures in excess of 55000 K (Feige 24, G 191–B2B). Being

originally discovered with IUE (Bruhweiler & Kondo, 1981), the heavy elements are extensively studied in UV and far UV spectra of the hottest DAs, which show the presence of absorption lines of C, N, O, Si, S, P, Fe and Ni (Sion et al., 1992; Barstow et al., 1993; Vennes et al., 1996). The heavy elements are separated to the photosphere by the radiative levitation. There is evidence for the stratification of Fe in the atmosphere of G 191–B2B (Barstow et al., 1999), Fe is stratified with increasing abundance at greater depth. Stratification of elements is obtained self-consistently in atmospheric model atmospheres with account for gravitational settling and radiative levitation (Dreizler & Wolf, 1999).

Cool DAZ degenerate stars are believed to accrete interstellar gas, which enriches their photospheres. A few DA stars display Ca, Mg, Fe lines both in the UV and in visible regions. They are G 74–7 (7300 K) (Lacombe et al., 1983; Billeres et al., 1997), G 29–38 (11000 K) (Koester et al., 1997), G 238–44 (20000 K) (Holberg et al., 1997). Some lines (Mg II λ 4481) originating from the excited lower level demonstrated that they cannot arise in the interstellar gas. Recently Zuckerman & Reid (1998) have observed 38 cool DA stars with HIRES on the Keck I telescope. They have searched for the Ca II K line which could indicate a gas accretion. They have found that the Ca II K line was registered in spectra of about 20 % of the stars. In this situation the border between DA and DAZ stars looks rather illusory. It is very important to get more information on the signs of the elements in the atmospheres of white dwarfs both from UV spectra and in visible ones using very high signal-to-noise spectroscopy. In the controversy between line-free DC and DA/DB stars such a spectroscopy has drastically reduced the number of DC stars (Greenstein, 1986).

In the medium-temperature atmospheres $\lesssim 20000$ K, as it is in 40 Eridani B, the radiative pressure is not so strong as to separate heavy elements and to enrich the photosphere. As it follows from the simulations by Chayers et al. (1995) of expected equilibrium abundances of heavy elements levitating up to the photosphere, in DA stars with a temperatures $\lesssim 20000$ K one may expect Al/H and Si/H $\lesssim 10^{-9}$, and other elements are less levitating at such low temperatures. The theory predicts all heavy elements in the photospheres of DA white dwarfs have to settle down by gravitational sedimentation, which is a very rapid and effective process. For instance, the settling time for metals at a temperature of 15000 K is about 3–4 days, and it is only 0.6 day for He (Paquette et al., 1986).

Another possibility of supplying the photospheres of DAs with heavy elements is a gas accretion (Alcock & Illarionov, 1980a; 1980b) from interstellar medium (ISM) or stellar winds from a companion in binaries. Accreting mass rate depends strongly on differ-

ential velocity V between a star and the local ISM, $\dot{M}_a \propto V^{-3}$. The distribution of the differential velocities between DA stars and the ISM is asymmetrical (Holberg et al., 1999), the distribution is nearly uniform between +80 and –20 km/s. This assumes that the lines measured are related to the stars or the local ISM disturbed by stellar winds. Basing on the central part of the distribution, it can be suggested that the relative velocities may be $\gtrsim \pm 20$ km/s. The interstellar gas accretion rate is $\dot{M}_a = 4\pi m_H \hat{n} (GM)^2 V^{-3} \approx 3.2 \cdot 10^{-16} \hat{n}_1 m_{0.6}^2 v_{20}^{-3} M_\odot/\text{y}$, where the star's mass is $m_{0.6} = M/0.6 M_\odot$, the relative velocity is $v_{20} = V/20$ km/s, the number density of the ISM (out of dependence on its ionization state) is $\hat{n}_1 = \hat{n}/1\text{cm}^{-3}$.

With regard to the interaction of stars with the ISM any star can be in one of the two states: i) the mass loss and ii) the ISM gas accretion. The mass loss of hot stars is much more effective than the radiative pressure in prevention of accretion. However in the case ii) where the star does accrete a gas, under some conditions the accretion may be eventually stopped at the border of magnetosphere and the gas can be expelled by the rotating magnetic field — the propeller (Shvartsman, 1970; 1971; Davidson & Ostriker, 1973; Illarionov & Sunyaev, 1975). Even if a magnetosphere is in the propeller regime, some portions of the gas may penetrate inside the magnetosphere and reach the stellar surface due to various plasma instabilities. A study of tracks of the elements in white dwarfs may help to understand their status of interaction with the ISM.

The photosphere temperature of 40 Eridani B is $T_e = 16500$ K. The radiative levitation cannot supply the photosphere with heavy elements, but accretion can. If the magnetic field discussed above is dipolar, it can prevent the accretion depending on the relative velocity V between the star and the ISM. Greenstein (1980) reported a discovery with IUE of an absorption line near $\lambda 1391$ with an equivalent width of 3 Å, which could be Si IV or, which is most probable, the (0, 5) transition of the H₂ Lyman band. The last interpretation suggests presence of cool gas in the upper atmosphere of the star with a column density $N(\text{H}_2) \sim 10^{15} \text{cm}^{-2}$ (Greenstein, 1980). In spite of this the line was not confirmed in the later IUE study (Bruhweiler & Kondo, 1983), the same feature has been reported to exist in other white dwarfs (Wegner, 1982). No stellar photospheric features have been reported by Holberg et al. (1998) in the IUE total co-added spectrum of 40 Eridani B. Only weak interstellar features due to Si II λ 1260, C II λ 1334, and O I λ 1302 have been detected there.

We have a good chance to check the theory and to search for the tracks of elements in 40 Eridani B in the visible range. The total exposure time over the 3 nights of the Zeeman observations was 5 hours. We shifted the grating by 30 – 50 Å on each night in order

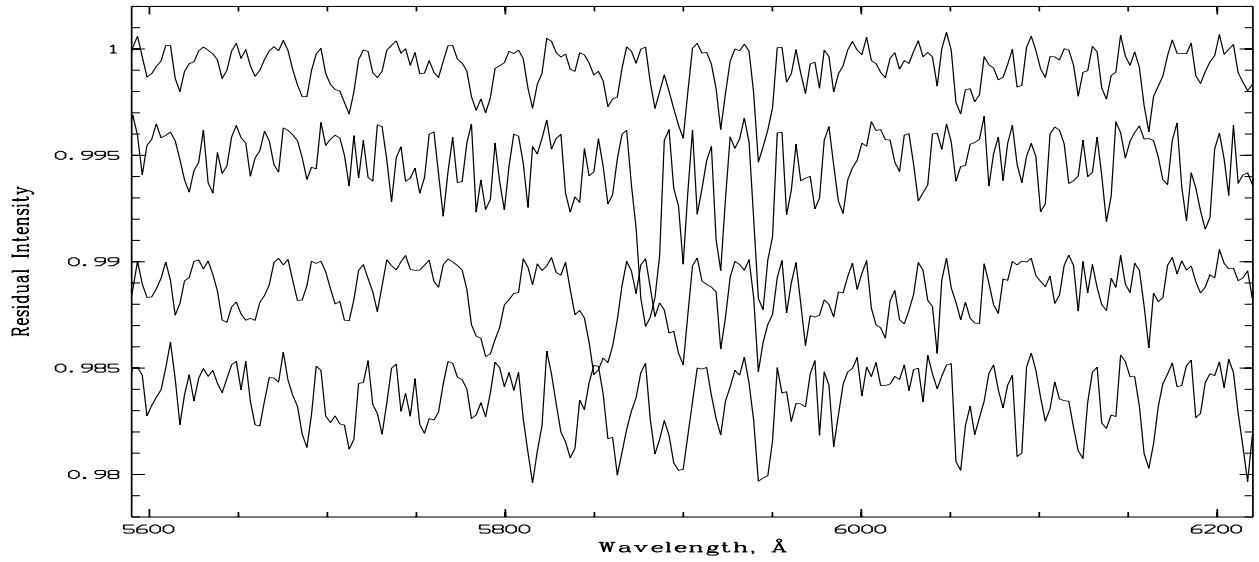


Fig. 11: The normalized sum spectra of 40 Eridani B obtained from bottom to top — in the 3-rd, 2-nd, 1-st nights and the total sum spectrum. The spectra are consequently shifted on 0.005.

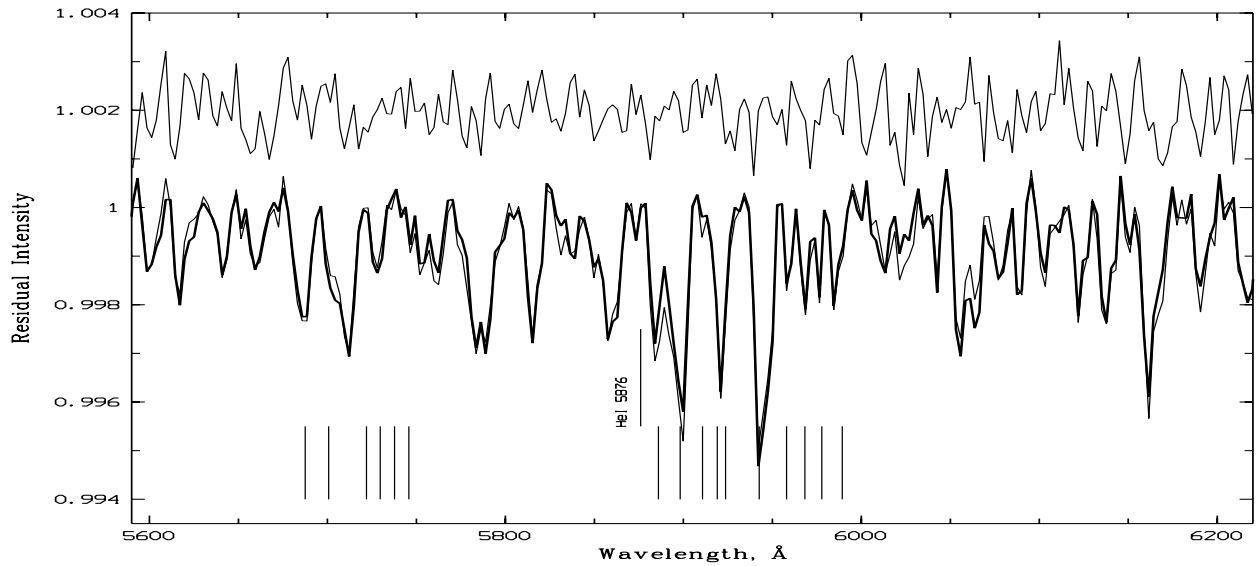


Fig. 12: The normalized sum total spectrum of 40 Eridani B (bold line), that without background subtraction (thin line) and the total background spectrum (shifted up). The sky background spectrum was divided into 20 for better visual inspection

to avoid the nonuniform pixel-to-pixel sensitivity of the CCD. The superflat, superbias and superdark images were prepared and standard procedures of spectrum reduction were applied. We obtained a summed unpolarized spectrum of the star (Fig. 10). In the range 5500 – 6000 Å about $4 \cdot 10^6$ counts obtained in the total spectrum, and about $1.5 \cdot 10^6 \div 2 \cdot 10^6$ counts in the blue < 4500 Å and red > 6500 Å ranges. The spectrum in the region 5600 – 6200 Å is shown in Fig. 11. There are 4 spectra — for the 3-rd, 2-nd, 1-st nights and the total spectrum in the figure from

bottom to upwards accordingly. The spectra were smoothed and normalized with a window of about 50 Å, so any information on broader spectral details was lost in the spectra. The spectral resolution in the summed spectra is comparatively low, 6 Å. Unfortunately the Ca II K line was beyond the spectral range registered (the main goal of the spectroscopy was to study the magnetic field, and hydrogen H α line was the most important).

One can see a number of weak absorption lines in the spectrum, and the strongest of them repeatedly

appeared in the spectrum of each night. In Fig. 12 we present the final background-subtracted spectrum (bold line) and that with no background subtraction (thin line) in the same spectral range, as well as the corresponding total background spectrum (top) which has been divided into 20 and shifted up for the best visual inspection. A special study of the background subtraction was carried out. We found that any possible errors in the background normalization and subtraction could not change the resulting absorption lines found in the 40 Eridani B. The Moon phases were 0.7 – 0.85 during these observations, and the background contribution in the spectrum was $\approx 1\%$.

In Fig. 12 are also shown positions of telluric lines (Curcio et al., 1964), they are either positions of the strongest line in the group of lines or positions of groups of lines convolved with our spectral resolution. In spite of the rather low resolution we certainly observe these lines in the spectrum. The expected position of the strongest He I line 5876 Å is also shown. This line intensity is less than 0.001. A preliminary inspection of this range and other ranges of the spectrum has shown that we observe numerous weak lines of Ca I, Na I, Fe I, Fe II, Mg I, Mg II, Si II at a level of intensities of 0.1 ÷ 0.5 %. The ultraweak absorption spectrum of the star corresponds to a temperature of 5000 – 8000 K, so they are not photospheric features. These lines could be interstellar by origin, but not all of them, because many lines have excited the low level, and Na I D₁, D₂ lines, for example, are not the strongest among other lines observed. An analysis of these absorption features will be made elsewhere. The signal-to-noise in the total spectrum is in the range 1000 – 2000, but the correct value can be found only after detailed identification of the spectrum.

We conclude preliminarily that a rich absorption spectrum of heavy traced elements is present in 40 Eridani B. Assuming that the photospheric He I line are broadened to FWHM ≈ 20 Å we find that its equivalent width is $W_\lambda < 10$ mÅ. In a weak absorption line approximation, $W_\lambda = \pi e^2 \lambda^2 N f / mc^2$, the upper limit of the He I line intensity gives the upper limit of the column number density of this element $N(\text{He I}) < 10^{11} \text{ cm}^{-2}$ or He abundance $N(\text{He})/N(\text{H}) < 10^{-7}$. This confirms the theory that He has indeed diffused under the photosphere in the hydrogen-rich degenerate.

The traced absorption spectrum does not agree with the photospheric temperature; this suggests that we have observed either i) the uppermost atmosphere gas in this star, or ii) circumstellar gas, or iii) interstellar gas. We believe that the traced heavy elements are supplied through the gas accretion process, this gas may come both from the interstellar medium and from the comparatively close companion 40 Eri C. The local ISM consists of a few fluxes (Bochkarev,

1990) which move with some dispersion in about similar directions. In the heliocentric frame the average velocity of the fluxes is 20 ÷ 30 km/s, and the common direction is $\alpha \sim 90^\circ$, $\delta \sim 0^\circ \div 10^\circ$. This direction is not far from that to 40 Eridani B. Comparing with the real radial velocity of the star (Reid, 1996), $V_r = -44$ km/s, we find that the relative velocity is high enough. Direct measurements of the ISM line of sight velocity have been obtained by Holberg et al. (1998), +7 km/s; this gives the differential radial velocity between the star and the ISM as 51 km/s. In a tangential direction the proper motion corresponds to a velocity of 94 km/s. We can find that the total relative velocity of 40 Eridani B and its local ISM is $V = 100 - 120$ km/s. Accepting a density of the ISM close to the Sun $\hat{n}_{0.1} = \hat{n}/0.1 \text{ cm}^{-3}$, find the mass accretion rate $\dot{M}_a \approx 2.2 \cdot 10^{-19} \hat{n}_{0.1} m_{0.6}^2 v_{100}^{-3} M_\odot/\text{y}$.

The companion of 40 Eridani C is an M4e dwarf separated from it by the $a = 40$ a.e. orbit. The companion's wind is captured by the white dwarf, and the capture radius is $R_c \approx 2GM/(V_{orb}^2 + V_w^2)$, where the relative orbital velocity $V_{orb} \approx 5$ km/s is much less than the probable stellar wind velocity from the companion, $V_w \sim 100$ km/s. One may expect the white dwarf to accrete the wind gas at a rate $\dot{M}_a = \dot{M}_w (\pi R_c^2 / 4\pi a^2) \approx 1.6 \cdot 10^{-4} m_{0.6} v_{100}^{-2}$. Assuming the mass loss rate in the wind of 40 Eridani C to be $\dot{M}_w \sim 10^{-15} M_\odot/\text{y}$, we obtain about the same value of the accretion rate as that found from ISM, $\dot{M}_a \sim 10^{-19} M_\odot/\text{y}$. Both the circumstellar gas density and its velocity field around 40 Eridani B may change in a rather complex way depending on the companions' winds interaction and orbital phase.

Using the above discussed magnetic field strength and rotational period we can find whether the accreting gas reaches the stellar surface or not. If the magnetic field is dipolar with the pole strength B_p , the Alfvén radius (radius of stopping of accretion) is $R_A^{7/2} = B_p^2 R^6 / \dot{M}_a (8GM)^{1/2}$, where the stellar radius $R \approx 9 \cdot 10^8$ cm. The co-rotation radius is $R_c^{1/3} = GMP^2 / 4\pi^2$, where P is the rotational period. The accretion is permitted when $R_A < R_c$ or $\dot{M}_a > \dot{M}_{cr} = 8^{-1/2} (2\pi)^{7/3} (GM)^{-5/3} P^{-7/3} B_p^2 R^6 \approx 9 \cdot 10^{-20} m_{0.6}^{-5/3} p_3^{-7/3} b_5^2 M_\odot/\text{y}$, where $p_3 = P/3$ hours, $b_5 = B_p/5$ kG.

We find that 40 Eridani B can accrete the gas both from the ISM and from the companions onto the surface. At the same time, because we have found that $\dot{M}_a \gtrsim \dot{M}_{cr}$, the accreting gas will form a circumstellar rotating envelope in the magnetosphere at a distance $r \sim R_A \sim 4 \cdot 10^{11}$ cm. The circumstellar gas can produce the ultraweak absorption spectrum observed.

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